

E83-10003

2. AgRISTARS

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✓ SYM-12-04306
✓ JSC-18245 169492
NASA CR-14877

A Joint Program for
Agriculture and
Resources Inventory
Surveys Through
Aerospace
Remote Sensing

6. MARCH 1982

Yield Model Development

SECOND GENERATION CROP YIELD MODELS REVIEW

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(E83-10003) SECOND GENERATION CROP YIELD
MODELS REVIEW (Missouri Univ.) 37 E
HC AC3/MF AC1

CSCL 02C

N83-12483

NOV 1982



Unclass

G3/43 00003

AGRISTARS
RM 200, FEDERAL BLDG.
600 E. CHERRY ST.
COLUMBIA, MISSOURI



1. Report No. YM-12-04306, JSC-18245	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Second Generation Crop Yield Models Review		5. Report Date March 1982	
		6. Performing Organization Code	
7. Author(s) T. Hodges		8. Performing Organization Report No.	
9. Performing Organization Name and Address USDA/U. of Missouri Rm 200, Federal Bldg. 600 E. Cherry St. Columbia, MO 65201		10. Work Unit No.	
12. Sponsoring Agency Name and Address NOAA Johnson Space Center/SK Houston, TX 77058		11. Contract or Grant No.	
15. Supplementary Notes		13. Type of Report and Period Covered	
16. Abstract Second generation yield models, including crop growth simulation models and plant process models, may be suitable for large area crop yield forecasting in the Yield Model Development project. This report defines subjective and objective criteria for model selection and reviews models which might be selected. Models may be selected (1) to provide submodels as input to other models, (2) for further development and testing, or (3) for immediate testing as forecasting tools. A plant process model may range in complexity from (A) several dozen submodels simulating (1) energy, carbohydrates, and minerals, (2) change in biomass of various organs, and (3) initiation and development of plant organs to (B) a few submodels simulating key physiological processes. The most complex models cannot be used directly in large area forecasting but may provide submodels which can be simplified for inclusion into simpler plant process models. In the report, both published and unpublished models which may be used for development or testing are reviewed. Several other models, currently under development, may become available at a later date.		14. Sponsoring Agency Code	
17. Key Words (Suggested by Author(s)) Crop Simulation Modeling Crop Physiology Models Large Area Yield Forecasting	18. Distribution Statement		
19. Security Classif. (of this report) Unclass.	20. Security Classif. (of this page) Unclass.	21. No. of Pages 36	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161

SECOND GENERATION CROP YIELD MODELS REVIEW

by

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March 23, 1982

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I. Introduction

This report was prepared in support of the Yield Model Development (YMD) Project of the Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS) program.

In the YMD project, crop yield models will be used for large area yield forecasting in the U.S. and in foreign areas both for midseason forecasts and for end-of-season estimates of crop yields. Numerous crop growth and yield models have been developed for a wide range of purposes in recent years. These models range in complexity from the most sophisticated simulators of plant growth, primarily intended for research into plant physiological interactions, to multiple regression models using only a few monthly weather variables to forecast regional crop yields.

In this report we will review plant-process models of a moderate level of complexity as candidates for application to large area yield forecasting. Identification and selection of such models presupposes some accepted standards for model evaluation. However, because of wide differences in philosophy among researchers working in plant-process yield modeling, complete agreement on such standards has not been reached. Therefore, we will propose a working set of standards for identifying and selecting plant-process yield models with potential for large area yield forecasting. We will then review some available models in terms of these criteria.

Other criteria were established by Wilson et al., (1980) for selecting statistically based crop yield models. The more quantitative of those criteria will also be used, when it is appropriate, for evaluation and selection of process based crop yield models.

II. Plant-Process Yield Modeling

Numerous plant processes have some degree of importance in determining crop yield variability under some range of environmental conditions. For large area yield forecasting we want those processes which can capture extreme variations which can occur over large areas.

The processes most basic to yield are photosynthesis and dry matter partitioning, as these together directly account for grain formation.

Phenology, leaf area expansion, floral development, and leaf senescence must be accounted for to accurately model photosynthesis and dry matter partitioning throughout a crop growth cycle. The number of grains per unit area, which comes from floral development, is needed to properly model the partitioning of dry matter to grain. Plant water status directly affects all the above processes and may be estimated from a soil water budget involving evapotranspiration and available moisture capacity of the soil.

Since these processes are highly interrelated, one may select a variety of different combinations of processes in modeling crop yields. For example, while one researcher might directly model photosynthesis, another might try to account for its effects by modeling tiller development, leaf area expansion, floral development, and water stress.

Generally plant-process yield models have been developed to predict yield at the level of an average plant in a specified field. Thus the input data required by these models include plant parameters specific to the variety or hybrid planted in some field and soils parameters describing the soil in that field.

For large area yield forecasting applications, requiring such varietal- and field-specific input data is not practical. This is because within the size of areas for which yield predictions may be made (approximately 2,500,000 hectares) each of several varieties of a major crop will be present on several soil types. Therefore plant and soil parameters which represent all or a substantial portion of the varieties or hybrids and of the soil types present in an area are required.

III. Model Selection Criteria

Models will be identified and evaluated. Some will be selected for immediate testing while others will be modified and eventually tested. Other models may supply process submodels to a new model. Models will be selected for testing on the basis of how well they meet the needs of the Yield Model Development project in the judgement of project personnel. To aid in that judgement some working standards are proposed. These standards will be used to identify plant-process yield models to be acquired for our purposes: for comparative testing; for further development and testing; for incorporation into large area yield estimation routines; or to supply subroutines to other models.

Other criteria may be added as additional insight is gained in this study. If any suitable candidate models are not included in this report, it is by oversight and the author requests any information available on such models.

Major considerations should include (1) theoretical accuracy, (2) completeness, (3) simplicity, (4) sophistication, (5) structure, (6) validation, and (7) timeliness. These will be described in detail in the following paragraphs. Additional considerations include public availability of computer code, geographic area of model applicability, probable accuracy of model estimates, applicability to large area yield forecasting, absence of subjective factors in a model, ability to acquire all necessary inputs for a model, and the cost of running a model.

Theoretical Accuracy. Theoretical accuracy refers to how well the model agrees with current plant physiological theory. Each component of a model should be in agreement with our best current theoretical understanding of how that plant process really works. Interactions between model components should reflect or at least, not contradict what is known about how those processes interact in real plants. Theoretical accuracy may be assessed by posing the following questions: (a) to what extent is the final yield (or an important measurable intermediate variable) in the model affected by the full range of variation of each submodel or input variable, (b) how much variability in predicted yield would be lost by compressing or simplifying any given submodel (or variable) into a simple equation (or variable), and (c) how frequent and important are the conditions under which any given submodel will respond differently

from the way a real plant responds. While a high degree of theoretical accuracy should increase the probability of a model performing well outside the set of conditions where it has been developed and tested, such a model will not necessarily give highly accurate yield estimates. This can only be determined by a testing program.

Completeness. Completeness of a model refers to how well that model is designed to meet its purpose or objectives considering the limitations under which it is to be used. This means that a model should include all those processes and environmental conditions which are critical to yield formation throughout a large area. A model may also include processes which do not usually directly affect yield but which affect critical processes under certain conditions and for which modeling theory is well developed. A model need not include processes or conditions for which required parameters or data are not readily available, if they affect yield for only a very small part of a large area.

Simplicity. Simplicity is a desirable characteristic of a model. Simplicity in model form and use of input data, and the availability of model input data are often associated with cost. Another very important advantage of model simplicity is the ability of the user to understand the concept, capabilities and limitations of the model. A thorough understanding allows the user to evaluate the model in the light of other information and to modify the model if necessary. A simple model will generally require less training and experience on the part of the user.

Sophistication. The sophistication of a model relates to the complexity of interactions between model processes and the degree of detail with which each process is simulated. A high degree of sophistication can make a model sensitive to the effects of many combinations of conditions. However sophistication can also reduce a model's simplicity and make the model difficult to understand and expensive to run. A model may also be unsuitable for large area yield forecasting if input data are required that are not readily available. In general a modeler must find a balance between simplicity and sophistication that is appropriate for a particular application.

Structure. Structure refers to how a model has been implemented in computer code. A properly structured model will be relatively easy to understand and needed changes (for evaluation, further development, or operational implementation) can be made quickly and accurately only if the model program has modularity (black box structure). An improperly structured model is practically impenetrable to everyone but its originators and proper documentation is all but impossible.

Structure should be characterized by clarity and simplicity of flow rather than by complex branching and looping. A common type of problem is a program where flags are used to select overlapping sections of code to calculate several somewhat different functions. Modification of the code to change one function may unexpectedly change the other functions as well.

The various processes or subprograms of the model should be isolated from each other (modularized) so that none of the subprograms need to know the internal structure of the other subprograms (i.e. they should be black boxes to each other). With this type of structure, changes in how a subprogram does something will remain isolated within that subprogram and will not "ripple" throughout the rest of the program.

Data flow within the program should be highly restricted so that each subroutine has access to just those variables required for its operations. When unneeded variables are passed to a subroutine, changes in that subroutine may unexpectedly affect those variables, causing a problem to appear in some other part of the program. It can be very time-consuming to trace those problems back to their origins.

Validation. Validation refers to the testing of a model on an independent data set. When this has been done, we have an empirical indication as to the model's applicability to years and/or locations other than those for which it was fitted or calibrated. If a model has not been validated, then some independent tests should be run on the model before it is definitely considered as a candidate for large area yield forecasting. None of the models reviewed in this report have been adequately tested over a wide range of conditions and locations. All of the models need some additional testing.

Timeliness. Timeliness refers to the capability of the model to produce projections of end-of-season yield or estimates of potential yield as needed throughout the growing season. For example the model should be capable of providing a reasonably reliable yield forecast as early as it is needed. Subsequent forecasts should occur as needed and when significant improvements in earlier forecasts are possible.

IV. Model Reviews Format

A. Title, Author, and Reference

This section gives the title(s) of the published report(s) on the model, the author(s), and the reference(s) for the publication(s).

B. Abstract or Summary

This section consists of the abstract or summary from the model publication.

C. Status and Applicability

This section indicates if (and how long ago) model development has been completed. If it is known, the availability and language of model computer code is reported. The geographic area and environmental conditions where the model should be applicable are indicated.

D. Model Design

This section presents the important characteristics of the model as reported in the manuscript. The time period used for model development and the time period selected for testing (if specified) are presented. Data requirements, which include location, meteorological variables, agricultural statistics and phenological information (if needed), are listed including basic derived agrometeorological parameters such as soil moisture and potential evapotranspiration. Finally, assumptions are usually made in model development with regard to technological changes, weather-technology interaction, crop calendars (biological or phenological time as opposed to fixed or calendar time) and other unique features which must be considered for application testing. Some assumptions are also presented in Section E.

E. Critique

A brief summary of the model is presented in Section E. Section B (Abstract) contains a synopsis of the paper while Section E (Critique) is the reviewer's assessment of the capabilities and limitations of the model. It is an attempt to highlight those features of the model which can be identified by the reviewer to provide guidance for further examination in the application testing of the model.

F. Author's Comments

This section is provided to include any additional comments by the model authors in the review of the model.

A. Title, Author and Reference

CORNF: A dynamic growth and development model for maize
(Zea mays L.)

by

M. Stapper and G. F. Arkin

Program and model documentation No. 80-2. Texas Agric. Exp. Station, Texas A & M University, College Station, Texas. U.S.A. (1980).

B. Summary

A dynamic simulation model (CORNF) was developed to simulate daily growth and development of maize plants grown in a wide range of environments. Photoperiod-temerature-genotype interactions are accounted for by introduction of a maturity rating system for maize genotypes. Nine maturity classes are distinguished. CORNF was tested at nine different latitudes across the U.S.A. Observed and simulated values were compared for phenological stages, dry matter production, grain yield, yield components, leaf appearance, leaf area and water use.

C. Status and Applicability

1. Status and Availability. The model Fortran code is listed in the documentation and is available upon request. The model was completed and published in 1980. Some work may be needed to adapt the model Fortran code to run on another computer system.
2. Applicability. The model is designed to simulate maize production anywhere maize is grown by choosing the right maturity class. The model should be well suited for large area yield forecasting work because of its relatively simple input and output requirements.

D. Model Design

The model consists of major subroutines interacting to calculate phenological stage, leaf area development, light interception, photosynthate partitioning, ear development and water balance components. Growing Degree Days are used to compute changes in the development of the plant and are, therefore, the controlling parameter of the model.

1. Model Development. The model was developed from material published in the literature and field data collected at Temple, Texas in 1978 and 1979. The model was calibrated with field data collected in 1979 at Temple (Texas), Manhattan (Kansas) and Swift Current (Saskatchewan, Can.).

2. Model Testing. The model was tested on data which had not been used in model development. Some data were collected in 1979 and others were published in the literature. Nine locations in the U.S.A. between latitudes 31 and 47 degrees were represented in the final test, with a total of 31 genotype-years: Texas (8), Missouri (1), Kansas (1), Illinois (5), Pennsylvania (4), Iowa (6) and North Dakota (6).
3. Input Data Requirements. Input data for the model include daily meteorological data, planting information and soils information. The daily meteorological data include: solar radiation, maximum and minimum temperatures, and rainfall. Planting data include: date of planting, planting density, planting depth, leaf area of the first leaf and latitude of the location. Soils data include: initial and potential extractable water from each soil layer, the thickness of each layer, and coefficient values for soil surface temperature and Stage 1 soil surface evaporation. The maturity classes for which the model is to be run must be specified.
4. Model Output. Model output consists of daily values of phenological stage, leaf stage, leaf area index, root depth, extractable soil moisture within the rooting depth, evapotranspiration, ratio of actual to potential extractable soil moisture, daily and accumulated heat units, accumulated plant dry weight, reserve carbohydrates, daily increase and accumulated grain weight, percent grain moisture, intercepted photosynthetically active radiation and mean daily temperature. A summary output gives grain yield per hectare, above ground dry matter production per hectare, and number and weight of kernels per plant.

E. Critique

This model has the level of complexity desired in a process model for estimation of large area yields. The major areas of physiological activity and some of their interactions are modeled. As noted by the authors, some potential water stress effects are not modeled. These effects are reduction of leaf area due to water stress and delay of anthesis due to water stress. Overall, the model test results were very good.

F. Author's Comments

The results obtained with CORNF confirm the value of modeling crop phenological development when simulating crop production. The simulated total number of leaves on a plant is the essential parameter in the phasic development of the plant. It is used in computations to determine the occurrence of tassel initiation, ear initiation, anthesis and maturity, as well as the size of each individual leaf. The leaf number is determined as a result of photoperiod-temperature-genotype interactions. These interactions are not yet fully understood. A maturity rating system for maize genotypes was introduced on simplified relationships between total leaf number and daylength. A relationship between total leaf number and temperature also exists, but could not be quantified.

Model validation indicated that one genotype might have to be fitted to different maturity classes in different environments. A particular genotype, however, always belongs to the same maturity class in a given region. This gave the following distribution of maturity classes (1-9) over North America: from 1 in Saskatchewan to 9 in southern Texas and from 6 in Nebraska to 2 in Pennsylvania.

The Growing Degree Day (GDD) concept is another source of errors. It neglects the effects of (a) differences between air (screen) and plant temperatures (e.g. water stress), (b) differences between day and night temperatures, (c) extreme temperatures and (d) changing threshold temperatures with advancing age of the plant. Two other effects that influence GDD are accounted for in a crude way. GDD's are corrected for daylength, based on an empirical relationship established while calibrating the model. Early in the season, when the growing point is close to the soil surface, daily GDD's are reduced under conditions when soil temperatures are expected to be lower than air temperatures.

The model simulates crop production under conditions where no serious nutrient stress exists. Water stress effects are incorporated in the following processes: photosynthesis, transpiration, leaf senescence (leaf area after anthesis), kernel number and root growth. These processes could not be made very sensitive to water stress because water stress is derived from the simulated soil water balance and rooting depth which have their shortcomings.

Dry matter and grain production were generally simulated well. Yield component simulations (kernel number and weight) were less accurate. Calculated kernel number tended to be higher than measured, especially in high evaporative demand climates. Lower kernel weights simulated under conditions of limited assimilate supply, however, compensated for this error. Grain yields were over-estimated when ample assimilates were available for an over-predicted number of kernels.

The model is a first version. CORNF can be improved when more detailed data become available, leading to a better understanding of the processes involved.

A. Title, Author and References

A MODEL FOR PREDICTING CORN YIELDS FROM CLIMATIC DATA

by R.W. Hill A.M. Asce, and R.J. Hanks,

ASAE Technical Paper No. 78-4030

For Presentation at the 1978 Summer Meeting

American Society of Agricultural Engineers

B. Abstract

The single most important factor that influences crop yields from one location to another, or from one year to the next, is moisture availability. A better understanding of how water influences yields is essential for maximizing yields through water management practices. The objective of this study was to develop a model that estimates crop yield as a function of moisture availability during selected periods of growth.

Data inputs include the amount of soil water in storage at the beginning of the season; available soil water storage capacity for the root zone; and daily values of rainfall, irrigation, maximum and minimum temperatures, and specific parameters for each cultivar that relates phenology to daylength and/or temperature. Yield is predicted as a function of the relative transpiration during each of the selected growth periods.

When the program is used for scheduling irrigation, the required amount and timing of irrigation water for any planting date is determined by simulating the effects of applying supplemental water in incremental amounts and times. The "best" resultant irrigation scheduling is indicated for any pre-selected yield level.

The program does not eliminate the need for field trials, but it can be used for identifying management practices that will maximize yields through water management or the avoidance of dry periods. Thus, field research can be concentrated on problem areas with resultant savings of time and money.

A. Title, Author and References

Model for Predicting Plant Yield as Influenced by Water Use

by R. J. Hanks

Agronomy Journal 66(1974): 660-665

B. Abstract

A model has been devised to predict plant yield, both total dry matter and grain, as a function of water use. The model is simple and inexpensive to run on a computer to determine seasonal yields as influenced by irrigation frequency and amount, rainfall, and soil water storage. A good fit of predicted vs. measured dry matter yield of sorghum (*Sorghum vulgare* L.) in Colorado, corn (*Zea mays* L.) dry matter and grain yields in Israel, and corn grain yields in Nebraska, with various water application treatments, was found. A basic assumption is that the ratio of actual to potential dry matter yield is directly related to the ratio of actual to potential transpiration. Evaporation from the soil is assumed to decrease with the square root of time after wetting as well as with the stage of growth. The shape of the relative yield-water use curve was found to be sensitive to the evaporation and transpiration assumptions made, but insensitive to the relation used to describe the influence of soil water status on transpiration.

C. Status and Applicability

1. Status and Availability. This model was published in 1974. No information is available as to further development on this model since 1974. If the 1974 version of the model is not available, it could be coded with a relatively small effort because of the simplicity of the model concept.
2. Applicability. The model estimates water stress effects on corn growth and grain yield. The model is potentially applicable wherever water is the dominant factor limiting corn growth and yield. In the U.S. corn belt, other factors appear to limit corn growth to a greater degree than water in many years so the model may not be well suited for this region. The model is intended for use in irrigation scheduling.

D. Model Design

The model consists of a soil moisture budget, and a function to estimate the contribution, during each growth period, of water stress to the reduction of actual grain yield below the potential yield level.

1. Model Development. The model was developed on data from irrigation treatments in Israel, and Colorado.

2. Model testing. The model was tested on data from 9 irrigation treatments at Mead, Nebraska in 1972. The model was also tested on data from California.
3. Input Data Requirements. The input data required by the model include daily weather data, crop parameters, soil parameters, and irrigation dates and amounts. Required daily weather data consist of rainfall, and potential evapotranspiration. Plant parameters are planting date, root growth parameters, growing degree days to reach each stage from planting to maturity, growth stage weighting coefficients for the yield function, and values of A and B for each growth stage where A relates potential transpiration to potential evapotranspiration and B relates potential soil evaporation to potential evapotranspiration. The soil parameters consist of initial and available soil moisture for each soil layer and maximum potential rooting depth.
4. Model Output. The model output consists of daily values of the soil moisture in each layer and actual and potential E and T and drainage. The model also gives a final estimate of grain and dry matter yield.

E. Critique

This model may have only limited applicability in the AgRISTARS large area yield estimation project because it considers only water stress effects on yield. Other factors which may be important include intercepted light, available nitrogen, high temperature stress, and frost damage.

F. Authors Comments

The model has been widely tested since the date of publication. It predicted corn yields well from irrigated and salinity tests in Utah, Colorado, Arizona, and California (Stewart et al., 1977). It has also predicted the effects of water stress on spring wheat yields in Utah. (Rasmussen and Hanks, 1976). Further tests on corn gave good predictions in Utah (Sorensen et al., 1980 and Wenda and Hanks, 1981). It also predicted the influence of irrigation on alfalfa yields (Hanks and Retta, 1980). A modification has been used to successfully predict range production under non-irrigated conditions, but water stress is the primary factor limiting growth (Wright and Hanks, 1981).

We have an operation manual which has the FORTRAN program (Retta and Hanks, 1980). We have work done on sensitivity in an M.S. thesis not yet published, indicating the model is not sensitive to the number of layers provided there are more than 2 and which also indicates the model is not very sensitive to the water content below which transpiration is taken to be less than potential transpiration.

This model was the basis for the modification to include the effects of sowing date on spring wheat yield (Hanks and Puckridge, 1980). This modification uses the same input data but predicts leaf area index and dry matter accumulation on a daily basis. It has not been tested except under the one Australian condition. We call this model HAPUC. This model (as well as PLANTGRO) is available from R.J. Hanks in FORTRAN and BASIC code.

Note that this model predicts relative yield as influenced by water stress only. Other factors that influence yield would change the potential yield (no water stress yield) and would not be accounted for in the model. Another factor not accounted for is upward flow of water from a water table (sub-irrigation).

If you want to account for nitrogen effects and water flow up from a water table, you need to go to a more sophisticated model (such as Watts and Hanks, 1980). This model is written in FORTRAN and is available from D.G. Watts (Univ. of Nebraska).

A. Title, Author and Reference

INITIAL VALIDATION OF A WINTER WHEAT SIMULATION MODEL

by S. J. Maas and G. F. Arkin

Technical Paper No. 80-4010 1980 Summer Meeting, American Society of Agricultural Engineers. San Antonio, Texas, June 15-18, 1980.

B. ABSTRACT

A model is described that simulates the daily growth and development of wheat plants based on temperature, photoperiod, soil moisture and population density. Information generated by the model during the growing season includes the length of the vegetative, reproductive and grain filling phases, number of productive and unproductive shoots per plant, and spikelet number, grain number and grain weight per head. As an initial test of accuracy, the model was executed for comparison with phenological, morphological, and yield data acquired from 10 fields sown to winter wheat during the 1978-79 growing season. All fields were located in the central portion of the United States -- 3 in South Dakota, 3 in Nebraska, 3 in Kansas, and 1 in Texas. Temperature data for the simulations were obtained from nearby weather stations, while precipitation and solar radiation were measured adjacent to the fields. Soil water conditions were determined for each field prior to sowing to allow initialization of the soil water balance portion of the model. An initial assessment of the accuracy of the model was made by comparing observed and simulated dates of emergence, floral initiation, anthesis, and maturity and values of shoots/plant, heads/plant, spikelets/head, grains/head, and weight/grain.

C. Status and Applicability

1. Status and Availability. The model Fortran code is available upon request. The model was completed and published in 1980. As the publication does not specify the type of computer or the dialect of Fortran there may be some work needed to run the model on another computer system. Additional information about the model program is available in Maas and Arkin (1980a).
2. Applicability. The model was developed for winter wheat and has a vernalization (cold) requirement which must be satisfied before jointing can occur; however, the model may be run for spring wheat by changing the input vernalization coefficients.

D. Model Design

The model grows a representative wheat plant by simulating emergence, winter kill effects, transpiration, soil moisture distribution, phenological development, leaf and tiller initiation and growth, floret initiation and development, and grain filling.

1. Model Development. The model was initially developed from results published in the literature for a number of spring and winter wheat varieties. The model was then adjusted and verified against detailed winter wheat data sets obtained at Bushland, Weslaco, and Temple, Texas and against data from North Platte, Nebraska.
2. Model Testing. The model was tested on data from 10 fields collected during the 1978-79 winter wheat growing season in South Dakota (3), Nebraska (3), Kansas (3), and Texas (1). Additional sensitivity testing is reported by Larsen (1981).
3. Input Data Requirements. Input data required include planting date, latitude, row and within-row spacing, planting depth, and 13 varietal parameters. The model also requires soils data including number of soil layers to be modeled, bare soil albedo, U and C for stage 1 evaporation, thickness of soil layers, and initial and maximum available soil moisture for each layer. Meteorological data required include maximum and minimum daily temperatures, daily solar radiation, rainfall, and snow depth. Snow depth is acquired to address the winter kill problem and for the soil moisture budget.
4. Model Output. The model is run on a daily basis and generates values for growth stage, tiller number, leaf area index, rooting depth, evapotranspiration, soil water balance, and snow melt. A summary output includes the number of tillers per plant, grains per plant, grain weight per plant, heads per area, yield per unit area, and yield components per tiller.

E. Critique

This model has about the level of complexity desired for large area yield modeling. For winter wheat, the authors noted that the model consistently predicted floral initiation (approximately jointing) about 2 weeks late, however they noted that the observed floral initiation dates might be in error.

The model does not include a photosynthesis subroutine, possibly because the authors felt that photosynthesis is not usually a primary limiting factor for wheat yield, but is itself limited by such factors as water stress, temperature, and mineral supply. However sometimes water and temperature stress limit yield through reduced leaf area duration, which can be modeled through photosynthesis and biomass accumulation. This model may require some revision to be suitable for spring wheat prediction in North Dakota but the effort may be worthwhile. Otherwise the leaf and tiller growth functions and the soil moisture budget may be suitable for incorporation into other models.

F. Authors Comments

No additional comments

A. Title, Author, and Reference

MODELLING DAILY DRY-MATTER PRODUCTION AND YIELD OF WINTER WHEAT*

Tom Hodges

B. ABSTRACT

Applicability of many plant growth models are limited because of the input data requirements. Photosynthesis and respiration equations were developed from meteorological data that could easily be obtained. The single crop parameter required was leaf area index. These equations were developed for winter wheat (*Triticum aestivum*, (L.)) from measurement of carbon dioxide exchange rate with field synthesis rates after jointing were attributed to sink enhancement of photosynthesis. Respiration was estimated as a photosynthesis-dependent growth component and a temperature-biomass dependent maintenance component. The equations predicted dry-matter accumulation. Head weight and yield equations were developed using predicted daily growth, LAI, and meteorological variables. Improvement of yield predicted was discussed.

*From, Photosynthesis, Growth, and Yield of Sorghum and Winter Wheat as Functions of Light, Temperature, Water, and Leaf Area. Chapter 1. Ph.D Dissertation Department of Agronomy, Kansas State University, Manhattan, Kansas, 1978. University Microfilms #78-21,869.

A. Title, Author, and Reference

MODELING COMPONENTS OF LEAF AREA IN WINTER WHEAT*

Jeff Baker

B. ABSTRACT

A leaf area index (LAI) term is used by many growth models to estimate various quantities such as photosynthesis and evapotranspiration. Because manual techniques for measuring LAI are extremely tedious, alternative methods of estimating LAI for these models are being sought. A model for predicting LAI was developed using the individual components of LAI: tillers/plant, leaves/tiller, leaf area/leaf, and leaf area/plant as a function of plant population, growth stage, water, and temperature. Equations were developed for winter wheat (*Triticum aestivum* L. em. Thell.) to provide a daily estimate of each component from easily obtainable meteorological data and data collected on plant growth in the field.

The model was tested on independent data sets from Texas, Arizona, and North Dakota. The model performed best when predicting LAI for fields in which soil moisture became limiting, but failed to match higher values of LAI on irrigated fields in which soil moisture did not become limiting, presumably because of an inability to adequately assess the effects of water on average leaf size.

* From Modeling Tiller Production and Components of Leaf Area in Winter Wheat as Affected by Temperature, Water, and Plant Population. Chapter 1. MS. Thesis Department of Agronomy, Kansas State University, Manhattan, Kansas, 1982.

A. Title, Author, and Reference

MODELING TILLER PRODUCTION AND SURVIVAL IN WINTER WHEAT*

Jeff Baker

B. ABSTRACT

Yield models requiring a leaf area index (LAI) term for the estimation of various quantities such as photosynthesis and evapotranspiration are hindered by the fact that methods of estimating LAI in the field are time consuming and costly. Because the leaves of a wheat crop grow on tillers, as the first step in ultimately developing an LAI model, a plant growth model was developed to predict tiller production and senescence for winter wheat (*Triticum aestivum* L. em. Thell) on a per plant basis as a function of plant population, growth stage, water, and temperature. The equations used in the model were developed from easily obtainable meteorological data and data collected in the field on five cultivars of winter wheat hand planted on two different planting dates. Using a concept developed by Friend (1965) from growth chamber experiments, increases in tillers/plant were modeled as following the Fibonacci series during the vegetative phase of growth until this rate was limited presumably by competition and/or limiting soil moisture. In order to adapt this concept to the field environment, accumulated daily thermal units (ΣTu where $Tu = \sum (T_{MAX} + T_{MIN})/2$) with a base temperature of 0°C were substituted for the chronological time used in Friend's experiments.

*From Modeling Tiller Production and Components of Leaf Area in Winter Wheat as Affected by Temperature, Water, and Plant Population. Chapter 2. Ms. Thesis Department of Agronomy, Kansas State University, Manhattan, Kansas, 1982.

C. Status and Applicability

1. **Status and Availability.** The tiller and leaf growth portion of the model was completed at the beginning of 1982. The current model card deck and test data set are now available but the model computer code is in the process of reprogramming for greater computer efficiency and ease of comprehension. The new program will probably be available sometime in 1982. The model is programmed in Fortran and could probably be run on another computer system with little effort. A modified version of the model uses satellite estimates of leaf area index instead of modeled values (Brakke and Kanemasu, 1979; Mohiuddin and Kanemasu, 1982).
2. **Applicability.** The model was developed for winter wheat and will require some adjustment, primarily of the phenology submodel to be used for spring wheat. The model may be suitable for use in those areas where solar radiation, water stress, and high temperatures are the most important factors limiting growth and yield.

D. Model Design

The model grows a representative wheat plant by simulating emergence, photosynthesis, respiration, transpiration, soil moisture distribution, phenological development, leaf and tiller initiation and growth, floret initiation and development, and grain filling. The model is designed to accept measured values of soil moisture, growth stage, and leaf area index throughout the season and adjust its simulation accordingly.

1. The model has three primary parts. The first part is a set of light interception, photosynthesis, and respiration equations derived from field chamber CO₂ exchange rate measurements made on various winter wheat cultivars at Manhattan, Kansas from 1973 to 1980. The second part is a set of tiller and leaf growth functions which provides daily LAI values to the first part of the model. The third part is a yield function which accumulates dry matter production over growth periods to estimate kernel number, kernel weight, and grain yield. The tiller and leaf growth functions were developed from two plantings each of five cultivars of winter wheat during the 1979-80 season at Manhattan, Kansas. The yield function was developed from eleven plantings of four winter wheat cultivars during the 1976-77 season at Manhattan, Kansas.

2. **Model Testing.** The first part of the model was tested for accuracy of biomass accumulation on winter wheat data from fourteen commercial fields in Riley, Finney, Ellsworth, and Colby counties in Kansas during 1975 through 1977. The second and third parts of the model were tested on 24 winter wheat fields during the 1979-80 season at Bushland and Vernon, Texas, on 12 irrigated spring wheat fields during the 1977-78 season at Phoenix, Arizona, and on 2 spring wheat fields during 1979 at Mandan, North Dakota. The authors concluded that the model worked best on fields where water stress limited leaf growth, probably because some degree of water stress was present on all of the developmental data.

3. Input Data Requirements. The model requires initial values of soil moisture for 5 layers of the soil profile as well as soil moisture content at field capacity and wilting point for each layer and two soil surface values controlling stage 1 evaporation. The model also requires daily values of solar radiation, maximum and minimum temperatures, and precipitation.

4. Model Output. The model is run on a daily basis and estimates daily values of soil moisture at each level, crop biomass per unit area, gross photosynthesis, daytime and nighttime respiration, and degree of water and temperature stress. The model also generates a final estimate of yield and yield components per unit area.

E. Critique

This model has about the level of complexity desired for large area yield modeling. For use in spring wheat yield forecasting, the phenology submodel would have to be replaced. In the latest version of the model, leaf growth, tiller growth, and head growth functions have been included. The requirement for initial soil moisture content can be avoided by running the model for the season previous to the season when the first yield estimates are required. The soil related constant values have to be estimated for large areas and may prove to be a problem.

F. Authors Comments

No additional comments.

A. Title, Author, and Reference

PREDICTION OF THE INFLUENCE OF WATER, SOWING DATE AND PLANTING DENSITY ON DRY MATTER PRODUCTION OF WHEAT

by R.J. Hanks and D.W. Puckridge, #Aust. J. Agric. Res., 1980, 31, 1-11.

B. Abstract

A water balance was used to calculate dry matter yields for wheat. The prediction used initial soil water, irrigation, rainfall and pan evaporation as inputs. Leaf area index (LAI) was estimated by an empirical equation and changes in LAI were determined by the ratio of predicted to potential transpiration and relative density. Time of sowing influenced time of maximum LAI. Dry matter production was calculated from equations relating LAI and photosynthesis.

The model was tested with data from wheat crops in South Australia which had been grown with large differences in water supply, planting density and sowing date between seasons. There was good agreement between predicted and measured production.

C. Status and Applicability

1. Status and Availability. The model was completed and published in 1980. Availability of the computer code is unknown and the paper does not specify the language or machine where the model was implemented. However, because of the simplicity of the model, it should not be too difficult to code again if it is not available.
2. Applicability. The model should be applicable in any area and year where moisture is the primary factor limiting spring wheat growth and yield. It was developed for spring wheat in South Australia and is based on earlier models (Hanks and Rasmussen, Rasmussen and Kanemasu) developed for spring wheat in Utah and winter wheat in Kansas.

D. Model Design

The model is designed to estimate total dry matter production or biomass of a wheat crop as a function of leaf area index (LAI) and degree of water stress. The model estimates daily values of LAI from assumptions about the date and value of maximum LAI and from calculated daily transpiration. Daily photosynthesis is then estimated from potential evaporation, LAI, and the ratio of calculated actual transpiration to calculated potential transpiration. Daily respiration is estimated from accumulated dry matter.

1. Model development. The authors used one irrigation treatment at the Waite Institute in Australia in 1969 as a standard year for model calibration.

2. Model testing. The model was tested on 5 irrigation treatments at Waite in 1969, 5 irrigation treatments at Palmer, Australia in 1977, and 4 planting date treatments at Waite in 1970 with generally good results.
3. Input Data Requirements. Required input data include planting date, daily or weekly potential evapotranspiration, daily precipitation or irrigation amounts, initial soil moisture, available soil moisture capacity with depth, and maximum LAI.
4. Model Output. The model estimates daily increase or decrease in LAI as a function of (1) days from planting, (2) planting density (3) date of beginning of appreciable growth (4) date and value of maximum LAI and (5) daily predicted and potential transpiration.

The model estimates daily photosynthesis and respiration from evaporation, predicted transpiration, predicted LAI, and predicted dry matter accumulation.

E. Critique

The model should give a reasonable estimate of yield for regions where it is calibrated, when water stress is the major factor limiting yield. When factors other than water stress are limiting yield, the model probably shouldn't do as well, however it may be possible to incorporate it into a yield estimation system for use when weather data indicates water stress is present. It may also be possible to modify the model by including in it more sophisticated leaf growth and phenology algorithms.

F. Author's Comments:

See comments under "A Model for Predicting Crop Yields from Climatic Data" by R.W. Hill and R.J. Hanks.

A. Title, Author, and Reference

SOYMOD/OARDC-

A DYNAMIC SIMULATOR OF SOYBEAN GROWTH, DEVELOPMENT, AND SEED YIELD:

1. Theory, Structure, and Validation, by G.E. Meyer, R.B. Curry,
J.G. Streeter, H.J. Mederski

Research Bulletin 1113, December 1979,
OHIO AGRICULTURAL RESEARCH AND DEVELOPMENT CENTER
Wooster, Ohio
U.S. 250 and Ohio 83 South

B. Summary

SOYMOD/OARDC is a detailed computer simulator of the soybean plant. It attempts to provide process description and visual description of the plant. An important key in this system is the breakdown and description of dry matter as the sum of four major entities: structural carbohydrate, available carbohydrate, starch, and protein. The mass balance system which encompasses the soil and aerial environment assumes that no mass is created or destroyed, but is transferred to or from the environment by the plant system. Material within the plant is partitioned among the morphological parts: leaf blades, stem-petioles, fruit, and roots. Available carbohydrate is transported in the plant, and the mechanism for this has been described using a system of coupled partial differential equations. The rates of material loss from one entity subsystem must be balanced by the rate of gain in another entity subsystem or returned to the environment.

Simulation of soybeans or plants in general requires an adequate description of the internal control system. This feature of the plant living system has eluded the crop modeling community for some time. A modest but satisfactory amount of dynamic control is provided by a plant carbon-nitrogen balance. By expressing the role of carbon in the nitrogen balance and concurrently, the role of nitrogen in the carbon balance, the two systems are linked and work together as a function of rate parameters and environmental conditions.

Carbon-nitrogen or dry matter-nitrogen ratios have little meaning to the total system unless they can be related to a general purpose of the system or specific subsystems. This purpose is assumed to be mass transport and mass conversion within the plant system, in response to specific cues to resolve internal deficiencies at given locations.

A complete internal control network has not been formulated. Before the internal control network can be expanded, some agreement must be reached on what additional components should be modeled or related to the rest of the system. The system should encompass all of the components possible.

SOYMOD/OARDC is an attempt to describe the soybean plant on the basis of carbon and nitrogen. This living system obviously depends on other nutrient components as well: phosphorous, potassium, and iron, for example. Future simulation efforts will address these.

The spectrum of simulated results from this model means that simpler soybean models can be questioned. Statistically based crop models with claims of accuracy and great utility should be judged in perspective. Inferential statistics were developed to aid in the testing of theories, but were never intended to designate what the theory should be.

The soybean model described in this manuscript is the original OARDC version to which reference should be made. Since May 1978, versions of SOYMOD/OARDC have been run on computers located at Wooster, Ohio, and Lincoln, Nebraska, under separate research programs. Over the past year, additional test and simulation runs have been performed on SOYMOD/OARDC. Not all of the results of these simulations are described here, but will be presented in future publications.

Copies of the model will be made available to state or federal agricultural researchers provided full credit is made public. However, the authors assume no liability for results generated on machines outside their domain. SOYMOD/OARDC and more recent versions are not available as an extension tool, since this simulator is most suitable for research and teaching involving physiological processes of the soybean.

C. Status and Applicability

1. Status and Availability. Versions of the model have been published in 1979 and 1980. The model is reported to be available to state and federal researchers. Some work might be needed to adapt the model to another computer system. Additional information on the model is available in Meyer and Curry (1981) and Meyer et al. (1981).
2. Applicability. This model is more complex than is needed for the AgRISTARS large area yield estimation program. However, some of the submodels in the model may be suitably simplified and incorporated into a new large area soybean yield process model.

D. Model Design

1. Model Development. The major components of the model are described in the summary. The various equations in the model are based on an extensive study of the soybean physiology literature, and on numerous growth chamber studies.

2. Model Testing. The various model subroutines were tested against field data collected in 1974, 1976, and 1977 for Beeson soybean (maturity group II) grown in Ohio. Although the test results were quite good, some areas were identified as needing further improvement including root growth and development, nitrogen partitioning, introduction of management practices, and the phenology submodel.
3. Input Data Requirements. The input data required include plant and planting data, climate data, and soils data. Plant data consist of varietal coefficients for the phenology submodel, rooting density characteristics for a given soil type, emergence date, row width, and plant spacing. Daily climate data include daylength, maximum and minimum air temperatures, dew point temperature, solar radiation, rainfall, and wind run. Soils data include soil type, soil water retention curve, bulk density, hydraulic conductivity, and initial soil water content.
4. Model Output. Daily model output includes a complete description of the simulated plant with number and size of various types of organs and distribution of carbohydrate and protein among the organs. A summary output includes summaries of all meteorological input data, dates key growth stages are reached and a final description of the plant including node number, dry weight distribution, seed weight, seed number, and total seed yield.

E. Critique

This model is reviewed primarily as an example of the most advanced crop growth and yield models. The model is probably far more sophisticated than is needed for large area yield modeling. Also some of the input data are not available over large areas. However, it is possible that some of the procedures in the model could be simplified for inclusion in a soybean process model.

F. Author's Comments:

On an IBM 370/model 3033, the model requires approximately 15 CPU seconds at a cost of \$2.20 per run (AGNET non-prime rate). The model performs best on this type of computer, although thought has been given to a condensed second-level microcomputer version.

A. Title, Author, and Reference

A Model for Predicting Soybean Yields from Climatic Data

by R. W. Hill, D. R. Johnson, and K. H. Ryan

Agronomy Journal 71(1979): 251-256

B. Abstract

The single most important factor that influences soybean (*Glycine max* (L.) Merr.) yields from one location to another, or from one year to the next, is moisture availability. A better understanding of how water influences yield is essential for maximizing yields through water management practices. The objective of this study was to develop a model that determines soybean yield as a function of moisture availability during four periods of growth.

Data inputs include the amount of soil water in storage at the beginning of the season, available soil water storage capacity for the root zone, and daily values of rainfall, irrigation, maximum and minimum temperatures, and specific parameters for each cultivar that relate phenology to daylength and temperature.

The program predicts yield as a function of the relative transpiration during each of four growth periods: emergence to beginning flowering; beginning flowering to beginning podfill; beginning podfill to end of flowering; end of flowering to maturity.

When the program is used for scheduling irrigation, the required amount and timing of irrigation water for any planting date is determined by simulating the effects of applying supplemental water in incremental amounts and times. The "best" resultant irrigation scheduling is indicated for any pre-selected yield level.

The program does not eliminate the need for field trials, but it can be used for identifying management practices that will maximize yields through water management or the avoidance of dry periods. Thus, field research can be concentrated on problem areas with resultant savings of time and money.

C. Status and Applicability

1. Status and Availability. The model was published in 1979. The model was coded in Fortran IV and a source deck may be available upon request. If a source deck is not available it would be a fairly small task to code the model again because of its simplicity.

2. Applicability. The model should give reasonable results in those cases where water is the major factor limiting soybean yields. However, in many areas, high or low temperature stress are major limiting factors and in these areas a water stress model may not capture changes in yield.

D. Model Design

The model coefficients were calibrated with yield data from a field study where soybean varieties from 3 maturity groups were planted at 4 dates at each of 3 locations in Missouri in 1971 and at 1 location in 1972.

1. Model Development. The model estimates relative plant dry matter accumulation from relative transpiration, i.e. the ratio of calculated transpiration to potential evapotranspiration. Growth stages are estimated from temperature and day length with the Major et al. (1975) soybean phenology model. Yield is estimated as a function of: relative transpiration during each of 5 growth stages, relative transpiration for the whole growing period, and a lodging factor due to excessive moisture during growth stages 2 and 3. Calculated transpiration is reduced if the soil moisture budget indicates that the available water is less than $\frac{1}{2}$ of the available water storage capacity.
2. Model Testing. The model was tested against yield data from 9 plantings of each maturity group in 1973 and one planting of each maturity group in 1976. The model had an R^2 of .96 or better against the test data for each maturity group.
3. Input Data Requirements. The input data required by the model include planting date, maturity group, initially available soil moisture and available soil moisture capacity for the root zone, and daily values of rainfall, irrigation, maximum and minimum temperatures, and solar radiation. If the soybean cultures are not in one of the five maturity groups then growth stage dates are needed as the phenology submodel does not have coefficients for other maturity groups.
4. Model Output. Model output consists of daily estimates of growth stage and soil moisture content and a final estimate of yield per unit area.

E. Critique

The model appears to be suitable for use in the large area yield forecasting program for areas where available moisture is the dominant factor limiting yields and where only soybean cultivars in

maturity groups I-V are grown. In much of the U.S., high and low temperature or solar radiation are important determinants of soybean yields. The model was designed to optimize irrigation scheduling rather than to forecast large area yields.

F. Authors Comments:

The model while used to illustrate the possibility of yield changes due to supplemental irrigation, is not limited to this. The calibration was completed with rainfed conditions while the verification data included only 1 irrigated experiment from Missouri. An additional verification was obtained from a linesource sprinkler experiment at Kaysville, Utah, 1980. The model matched the bean yields quite well for the intermediate to high irrigation treatments with an $R^2=88\%$ overall treatment (uncorrected for the mean). The model predicted yields were considerably lower than the observed yields on the nonirrigated plot.

The model uses "potential" yield levels which correspond to reasonably good management practices such as weed control, inoculation, etc. These should be adjusted to better match a particular region's expected high yield potentials. The simplicity of the model makes it a relatively easy task to recalibrate with locally available data.

The computer program as written can calculate evapotranspiration by any one of 5 different methods ranging from pan evaporation to the Penman combination equation, depending on data availability and preference of the user. Additional crops (corn, alfalfa and wheat) have been added to the model as of the present.

A. Title, Author, and Reference

WHEAT GROWTH AND YIELD MODEL: FORTRAN PROGRAM

J.T. Ritchie, Unpublished

B. Abstract

None available

C. Status and Applicability

1. **Status and Availability.** The model has not been published and will probably receive some further development before it is published. A working fortran program and test data set are available for testing or application. The model is intended for use on winter and spring wheat. It is now being altered for winter and spring barley.
2. **Applicability.** The model should be applicable anywhere that a wheat variety is grown provided that genetic coefficients are available for that variety.

D. Model Design

The model grows a representative wheat plant by simulating emergence, leaf growth and senescence, biomass, soil evaporation, transpiration, soil moisture distribution, phenological development, tiller number, grain number and grain filling. Each process is simulated for each day based on the previous values for all the processes.

1. **Model Development.** The model was developed from published reports and published and unpublished data for winter wheat and spring wheat in North America, Europe, South Africa, and Australia. For each process, the form of the equations and the values of coefficients were based on physiological theory and experimental data from both controlled environment and field conditions.
2. **Model Testing.** The model has been used or tested by several research groups on a variety of data sets with encouraging results.
3. **Input Data Requirements.** The model requires initial soil parameters, plant genetic parameters, latitude, planting date, and planting density. It also requires daily solar radiation, rainfall, maximum and minimum temperatures, and irrigation amounts if the crop was irrigated.

4. Model Output. Output from the model consists of daily values of soil moisture distribution, leaf and tiller number and dry weight, above ground plant dry weight, growth stage, grain number, and grain weight. The model also produces a summary output of kernel weight, grain number per unit area and yield per unit area.

E. Critique

The model is based on sound theoretical principles and the major plant processes contributing to yield variation are included. Although the model has not been published or documented, it has been tested independently at several locations with encouraging results. Genetic coefficients are available for 44 varieties of winter wheat. Having a range of values of genetic coefficients available may simplify the problem of getting values of these coefficients for large area yield estimation applications. Like the other available physiological models, this model has not been adequately tested so it is not possible to tell how accurately it will estimate yield under a variety of conditions.

F. Authors Comments:

The model is available to any potential user in its present state. We only request that users communicate problems associated with its use for possible improvements. The March, 1982 version has not been changed much from our version of a few months before then, so we are hopeful that the model will not be changed so frequently as it was during 1980 and 1981. The model is not accurate in estimating tiller and head number, but those numbers are not critical to yield estimation for this model. We anticipate model documentation in 1982.

A. Title, Author, and Reference

A Law of the Minimum Spring Wheat Yield Model

R.B. Cate and D.E. Phinney

Unpublished

B. Abstract

No abstract available

C. Status and Applicability

1. **Status and Availability.** The model was developed in 1979 and has not been modified since then. Fortran programs are available to run the model with existing coefficients or to rederive the coefficients.
2. **Applicability.** The model was developed and tested on the U.S. Great Plains spring wheat region. It has not been tested on any other areas so its range of applicability is unknown.

D. Model Design.

The model is based on Liebig's Law of the Minimum or Law of Limiting Factors. Spring wheat yield in crop reporting districts (CRD's) is assumed to be limited by the lowest of several factors, each calculated over several growth periods. The growth periods are calculated with the Robertson spring wheat phenology model using Feyerherm's planting model to get a planting date. The limiting factors are (available) nitrogen (based on estimated soil nitrogen, applied nitrogen, and estimated soil moisture) from planting to jointing, (2) from jointing to heading, and (3) from heading to maturity, and (4) average temperature from milk stage to maturity.

Trend is accounted for by using yearly values of Feyerherm's relative yielding ability (VYA) factor for CRDs and by increases in applied nitrogen.

1. **Model Development.** The model coefficients were derived using a maximum likelihood algorithm. Developmental data consisted of meteorological data, and crop data at the CRD level. Crop data included average yearly planting dates, yield values, applied nitrogen values, and VYA factor values for CRDs in North Dakota, South Dakota, Montana, and Minnesota for 1955 to 1966. Meteorological data included mean daily temperatures, and rainfall for estimated growth periods at the CRD level.
2. **Model Testing.** The model was tested with same type of data and over the same regions on the years 1967 to 1976 with good results.

3. Input Data Requirements. The input data required to run the model for CRD's where the model has been derived include daily temperatures and rainfall representing that CRD, nitrogen applied in the CRD, and average VYA for the varieties planted in the CRD in a given year. Values from one or several weather stations may be used to represent a CRD, nitrogen sales data may be used to estimate applied nitrogen, relative yield ability may be derived from varietal test results weighted by acreage planted to each variety. The developmental and test data sets were prepared by Dr. Arlen Feyerherm at Kansas State University for a spring wheat yield model based on a least squares fitting approach.
4. Model Output. Model output for a year and CRD consists of the value of each limiting factor and the maximum yield permitted by the most limiting factor.

E. Critique

The model is based on sound physiological principles. It performed well when tested on the 1967-1976 years in the northern U.S. Great Plains. The model has not been tested on any other regions so its geographic range is unknown. Availability of applied nitrogen and varietal yielding information may be a problem in some regions, but should be available for 1977 to the present for the U.S. Great Plains. The model should be considered for testing, as is, or should be refitted on more recent years if resources are available. Additional information on the model is available in Cate et. al (1979).

F. Author's Comments

No additional comments.

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